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DEVELOPMENT OF TERMINATION AND UTILIZATION CONCEPTS FOR FLAT CONDUCTOR CABLES

Volume III

Cost Study Comparison, Flat Versus Round Conductor Cable

D6-40711-3

July 1972

Distribution of this report is provided in the interest of information exchange. Responsibility for the contents resides in the organization that prepared it.

Prepared under contract NAS9-12062 by
THE BOEING COMPANY
Seattle, Washington 98124

for

Manned Spacecraft Center, Houston
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FOREWORD

This is volume III of a three-volume report prepared under contract NAS9-12062, "Development of Termination and Utilization Concepts for Flat Conductor Cables."

The other two volumes are:

Volume I (D6-40711-1)	Development of Low-Profile Flat Conductor Cable Connecting Device and Permanent Splice
Volume II (D6-40711-2)	Utilization of Small-Gage-Wire Round Conductor Cable

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DEVELOPMENT OF TERMINATION AND UTILIZATION CONCEPTS FOR FLAT CONDUCTOR CABLES

Volume III

Cost Study Comparison, Flat Versus Round Conductor Cable

The Boeing Company
Seattle, Washington 98124

SUMMARY

A cost study comparing flat conductor cable (FCC) with small-gage wire (SGW) and conventional round conductor cable (RCC) is included. This study was based on a vehicle wiring system consisting of 110 000 ft of conventional RCC equally divided between AWG sizes 20, 22, and 24 using MIL-W-81044-type wire and MIL-C-26500 circular connectors. Basic cost data were developed on a similar-sized commercial jet airplane wiring system; on a previous company R&D program in which advanced wiring techniques were carried through equivalent installations on an airplane mockup; and on data developed on typical average bundles during this program.

Various cost elements included in this study were engineering labor, operations (manufacturing) labor, material costs, and cost impact on payload. Engineering labor includes design, wiring system integration, wiring diagrams and cable assembly drawings, wire installations, and other related supporting functions such as the electronic data processing for the wiring. Operations labor includes mockup, tooling and production planning, fabrication, assembly, installation, and quality control. ~~Materials~~ Cost impact on payload is the conversion of wiring system weight variations through use of different wiring concepts to program payload benefits in terms of dollars.

The cost elements provide a base for measuring the "total value of technology" so that each wiring concept may be compared with any other concept included in the study. Results indicate that the effects on vehicle manufacturing costs vary from a reduction of $1 400 to an increase of $56 000 per vehicle, as compared to conventional RCC. However, based on a $416.8/lb value of payload (space shuttle program), the "total value of technology" indicates that the value of all the new-technology concepts far exceeds the conventional wiring system.

INTRODUCTION

In any new technological development, progress is first directed at evaluating the technical aspects of the development. Prior to full exploitation, the economic impact of the development must be determined to assess penalty and payoff factors. The economics of the new technology must be studied and compared with current technology. In this program, the comparison was reduced ultimately to a comparison of costs per wire segment—any length of wire with two ends terminated.

For this cost study, a comparison was made between conventional round conductor cable (RCC) of AWG 20, 22, and 24 against flat conductor cable (FCC) and against AWG 30 small-gage wire (SGW). The comparison was made on a basis of 10 vehicles with each vehicle using approximately 100 000 feet of wiring and 2000 connectors. The spread of wire size and connectors was based on a commercial airplane having similar quantities of wire and connectors. Due to the limited quantities per vehicle and the fleet size (10 vehicles) the cost of materials does not benefit from quantity procurement, and fabrication and installation costs do not benefit from learning curves.

This study was based on data from recent relevant R&D studies and from specific studies directed for the program. The data were amended to suit the vehicle parameters and updated to 1972 dollar values.

STUDY PARAMETERS

727-100 AIRPLANE MOCKUP

To establish a basic comparison between an actual FCC installation and a conventional RCC installation, an FCC installation in raceway T1 of the 727-100 airplane mockup was analyzed. This installation had been used prior to this program to develop fabrication and installation techniques for FCC. Table 1 compares wire details of FCC and standard RCC for this application.

The FCC in the T1 raceway installation was terminated by insulation-piercing crimp contacts developed by A-MP, by welded contacts incorporated in the Cannon three-wafer environmental connector, and by having FCC ends transitioned to RCC with crimped contacts (table 2).

A time analysis for fabrication, assembly, and installation of the FCC was made during development of the mockup. The man-hours required for conventional round wire were based on rates established by industrial engineering time studies.

To obtain a realistic comparison between FCC and RCC that would be applicable to this program, it was necessary to take one system and develop rates for that system only. Table 3 summarizes an analysis comparing conventional RCC with equivalent FCC using the A-MP Unyt-type connector and 2-in. 19-conductor FCC throughout. Figures 1 through 5 show some of the salient features of the 727-100 mockup installation.

TABLE 1.—727-100 AIRPLANE T1 RACEWAY WIRE COMPARISON

FCC to MIL-C-55543, Kapton/FEP insulated					RCC to MIL-W-81044/16	
Width, in.	Conductors	Wire size, AWG	Cable length, ft	Conductor length, ft	Wire size, AWG	Conductor length, ft
2	9	21	695.5	6 259.5	20	6 259.5
2	19	25	455.5	8 654.5	24	8 654.5
1	17	28	73.5	1 249.5	24	1 249.5
			Total	16 163.5		16 163.5
Average cable length, ft				64	64	
Total conductor weight, lb				35.39	45.628	
Bundles per layer				19	19	

TABLE 2.—727-100 AIRPLANE T1 RACEWAY WIRE TERMINATIONS DATA

Connector type	Number of contacts
FCC	
36 FCC connectors for FCC	
2-in. by 9-conductor, AWG 21, FCC, A-MP, crimp-through insulation	692 (socket)
2-in. by 19-conductor, AWG 25, FCC, A-MP, crimp-through insulation	
1-in. by 17-conductor, AWG 28, FCC, Cannon, three-wafer, welded	102
30 FCC connectors for RCC A-MP transition	590 (pin)
RCC	
Crimped contacts per MIL-C-26636	692 (socket) 590 (pin)

TABLE 3.—727-100 MOCKUP FABRICATION AND ASSEMBLY COMPARISON

RCC conventional bundle		FCC equivalent with A-MP Unyt FCC connector	
Function	Man-hours	Function	Man-hours
Prepare, cut, and code wire	5.5	Measure and cut cable	1.583
Strip and crimp first end	4.2	Crimp contact	1.267
Identify wire and tie out bundles	7.2	Identify	0.95
Strip, crimp, and assemble connector second end	7.2	Assemble connector	0.95
Total	24.1	Total	4.75

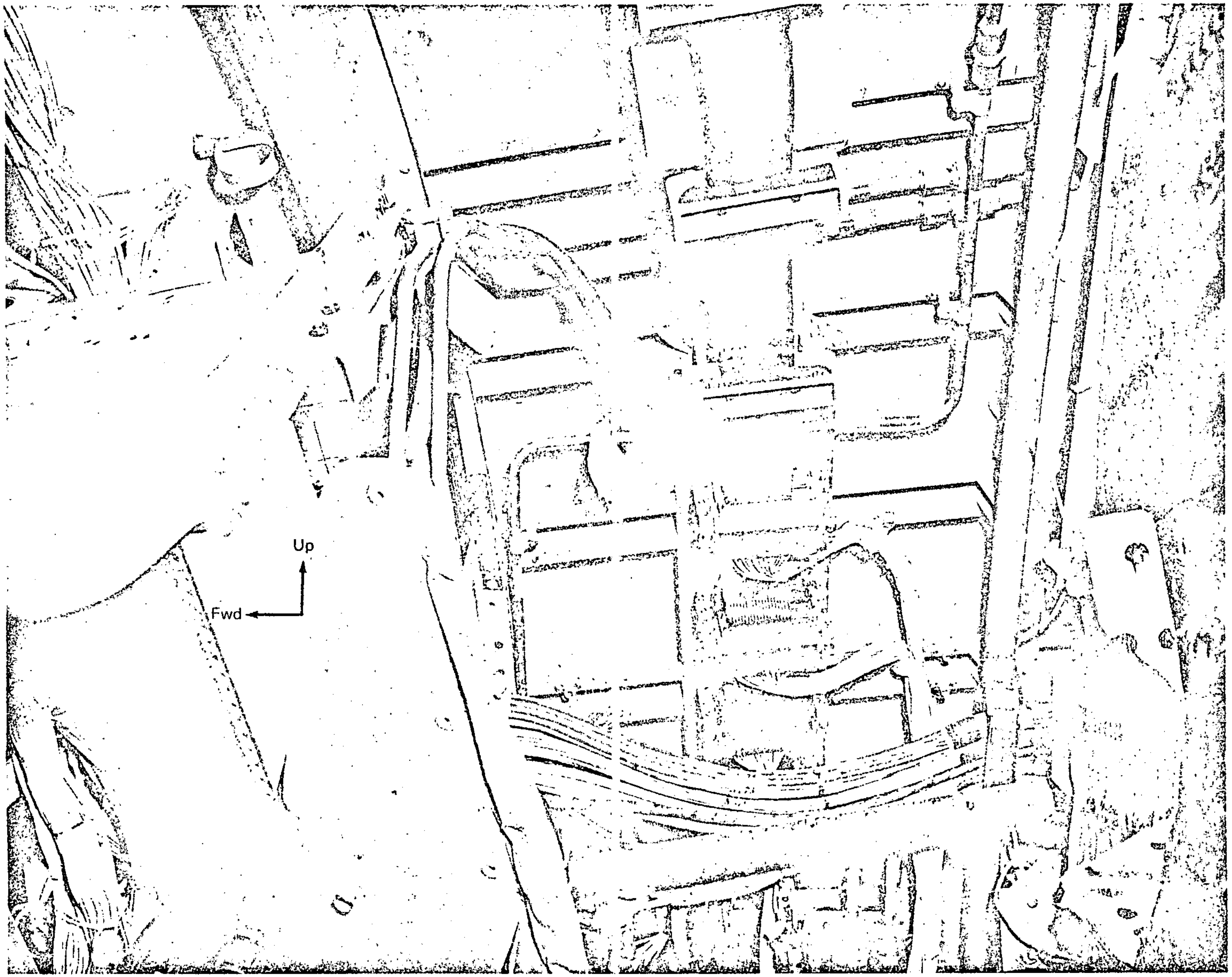


FIGURE 1.—PILOTS' COMPARTMENT—TRANSITION CONNECTORS, FCC TO RCC

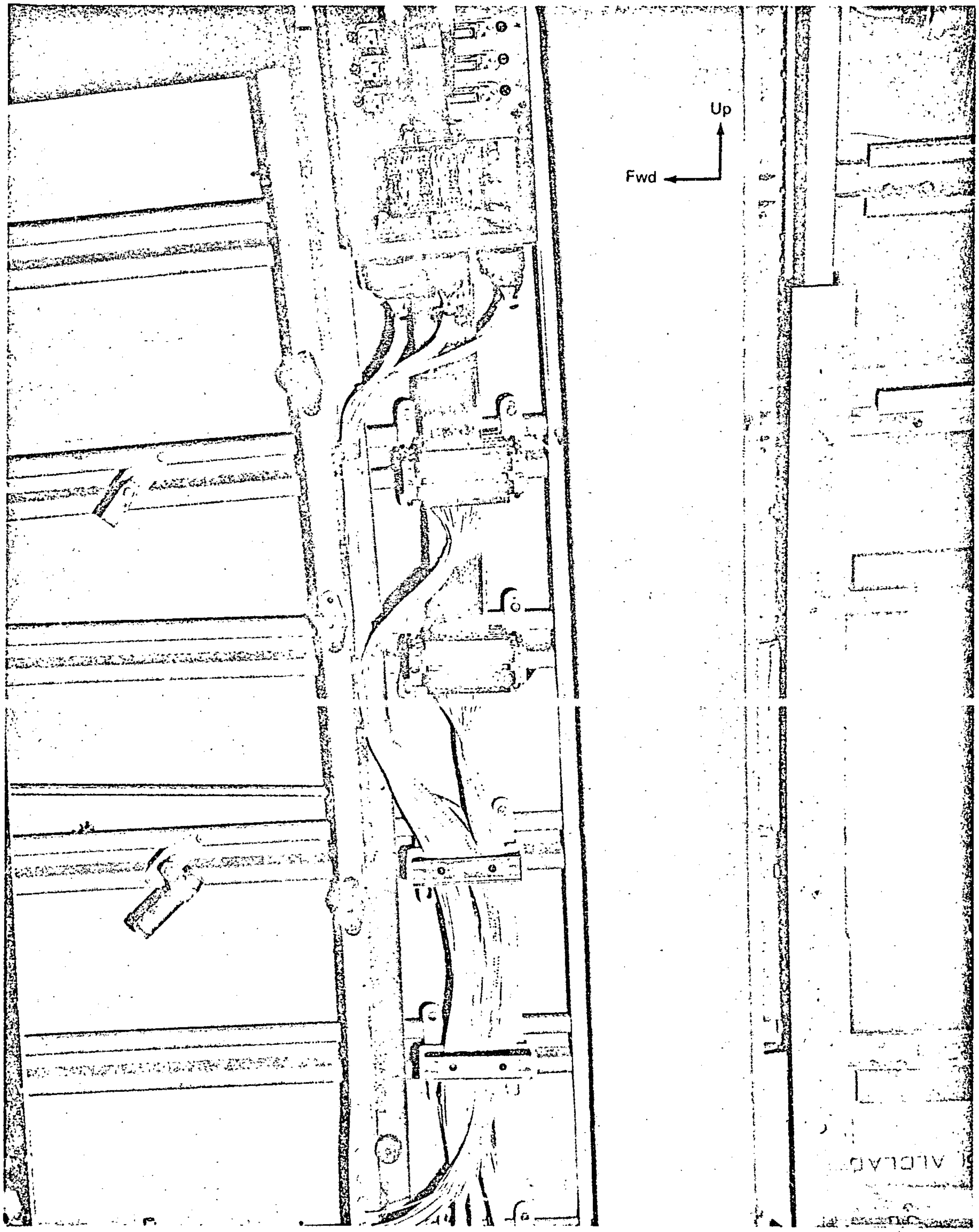


FIGURE 2.–TERMINAL JUNCTION BOX AND TRANSITION CONNECTORS

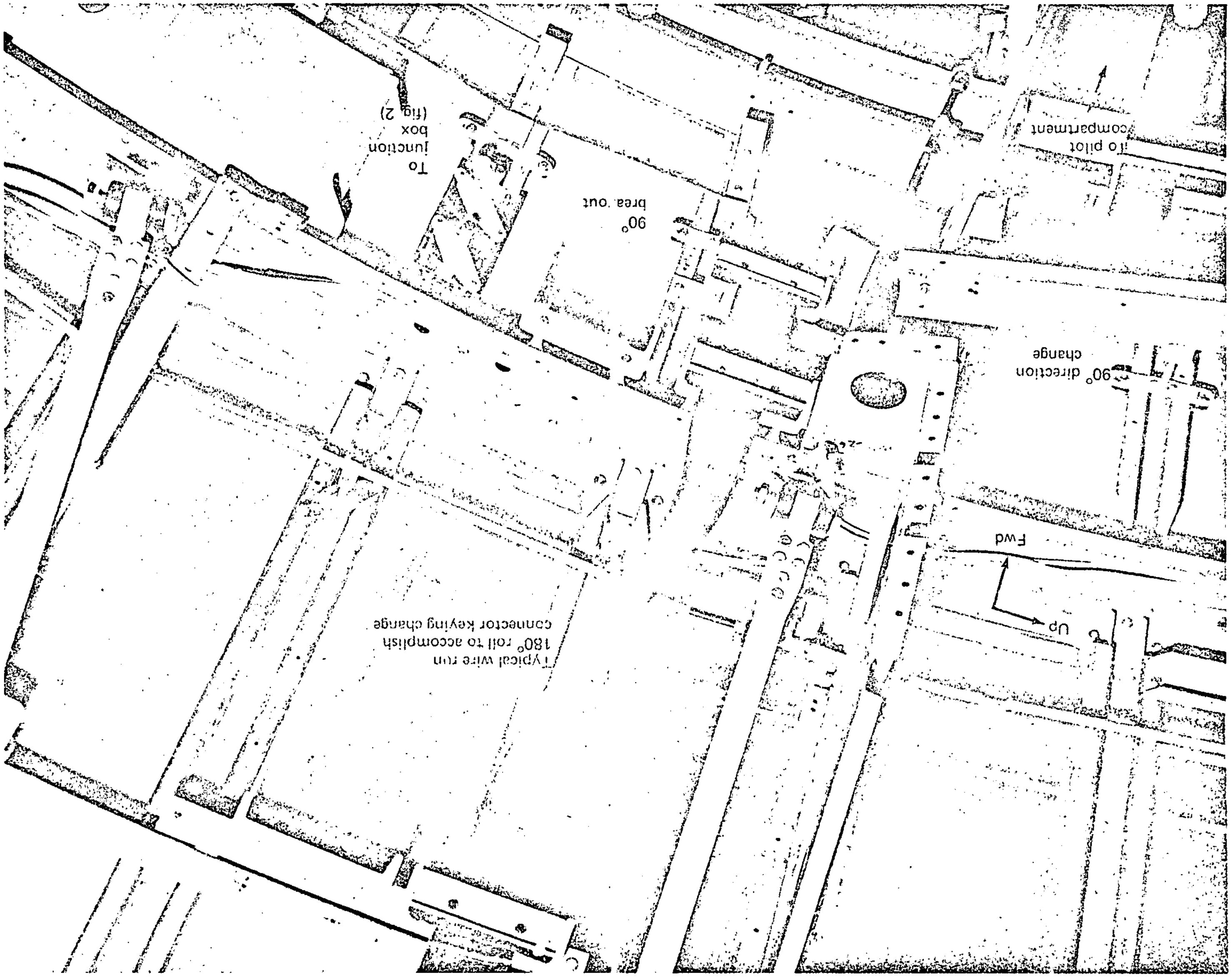


FIGURE 3.—ROUTING POSSIBILITIES

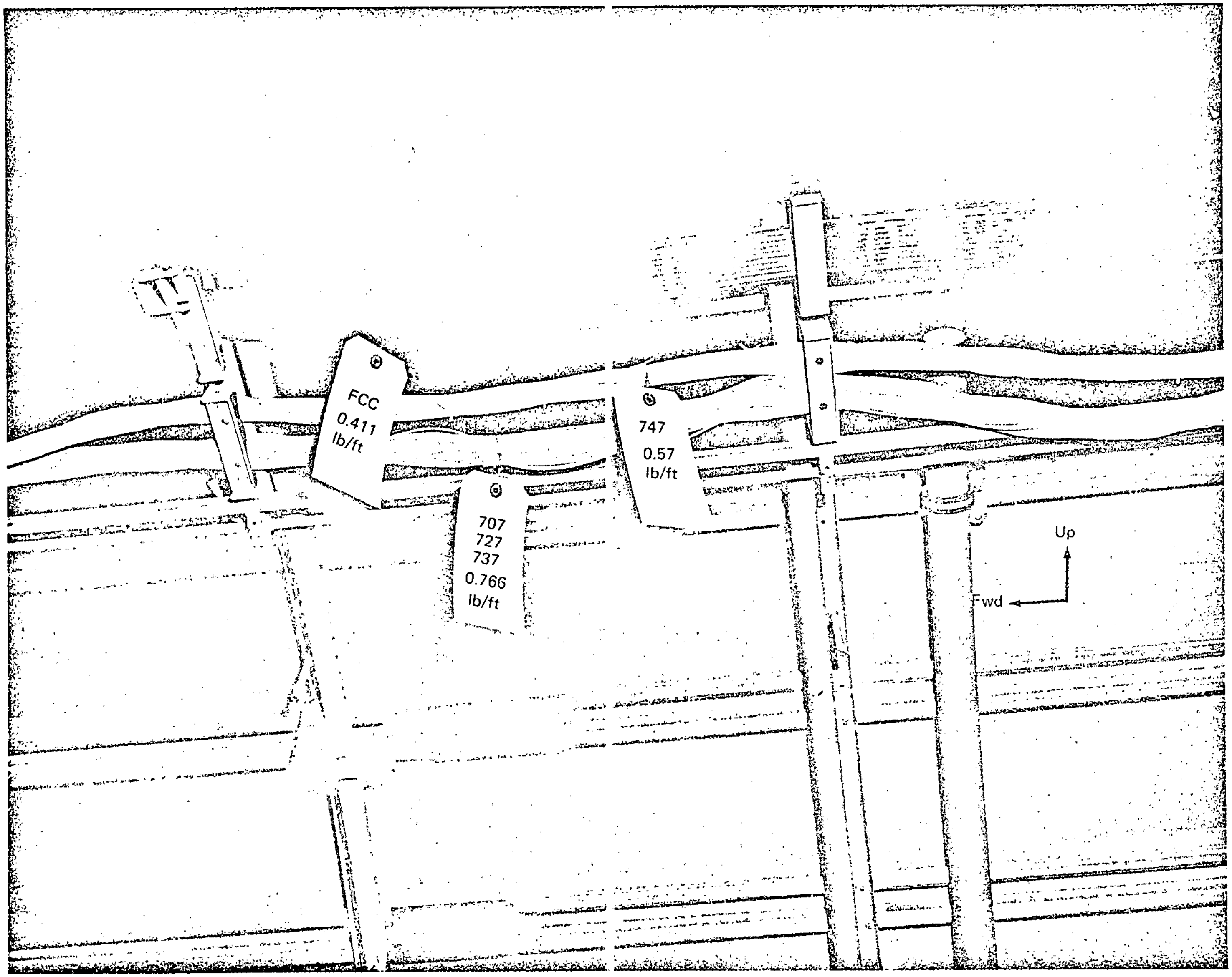


FIGURE 4.—WIRE RUN COMPARISON—FCC AND RCC

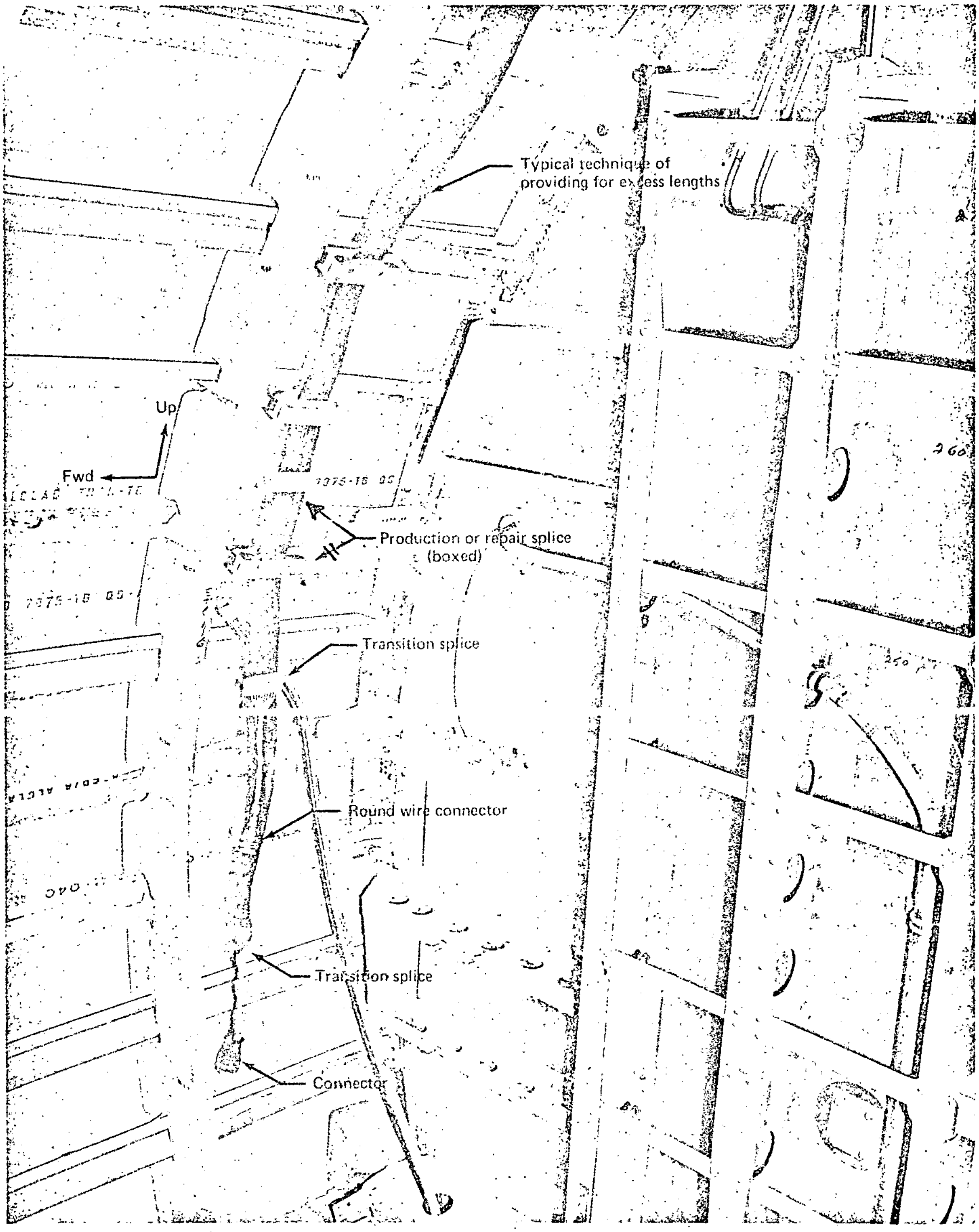


FIGURE 5.—TRANSITION SPLICE

DEVELOPMENT OF BASIC RATES

For the cost study, it was established that the wire size, function, and distribution of wiring in the vehicle would be similar to an equivalent-sized commercial airplane. Accordingly, an analysis of the wire sizes, lengths, and weights within several commercial airplane models were evaluated. Results given in table 4 are considered to be applicable. It is evident that the three smaller gages (AWG 20, 22, and 24) predominate. Confining the study to these sizes will not introduce disproportionate errors.

TABLE 4.–WIRE SIZES, LENGTHS, AND WEIGHTS

1	2	4	6	8	10	12	14	16	18	20	22	24	Total
74	264	341	220	713	923	1 252	978	3 911	5 715	36 105	44 831	32 233	127 501 ft
5.16	73.92	55.47	24.84	51.34	40.13	35.82	17.30	47.68	60.13	289.88	331.18	97.50	1 150 lb
Wire size, AWG													

Further, for small-gage wire application, only size AWG 24 can be replaced with AWG 30; AWG 20 and 22 are current or voltage drop limited so they must remain unchanged.

In analyzing the cost of wiring for each operation, such as fabrication, assembly, and installation, it is desirable to relate all functions to some common denominator. For wiring, a wire segment (i.e., a single wire of any length) is considered to be satisfactory. Therefore, the numbers of wire segments and wire bundles for the study vehicle have been determined, along with the man-hours for conventional RCC materials and installations (see table 5). The factors were evolved from production records.

TABLE 5.–WIRE DATA

Wire segments (average wire count)	18 500
Number of wire bundles	330
Number of wires per bundle	56
Man-hours required	18 000
Man-hours per wire segment	0.97

In arriving at the figures, consideration was given to the total number of vehicles, in this case only 10. The man-hours per wire segment of 0.97 is high relative to production runs. Typically, average figures of 0.5, varying to as low as 0.2, are possible on production runs.

The cost involved in wiring is divided into the two functions of engineering and operations. These are further subdivided:

- Engineerinng
  - Design

- Electrical/electronic integration
- Cable assembly drawings
- Installation
- Electronic data processing—wiring

- Operations
  - Mockup
  - Tooling and production planning
  - Fabrication
  - Assembly
  - Installation
  - Quality control

The proportion of the cost of one function (engineering) over the other (operations) varies considerably from the first vehicle to the nth vehicle, as would the actual cost. For example, initially engineering would be as high as 50% of the high initial cost, but, by the nth vehicle, the engineering share would be a small portion of the low final cost. Therefore, it was considered realistic for this program to apportion the costs on a basis of engineering 33.3% and operations 66.7% of the total cost.

In arriving at a cost per wire segment, consideration was given to the special nature of the vehicle, the reliability requirements, and other stringent factors as well as to the limited production. The figure of $10 per segment selected compares with figures for production runs that typically range from $7 per segment to $2 per segment (see table 6).

TABLE 6.—COST BREAKDOWN BY FUNCTIONS

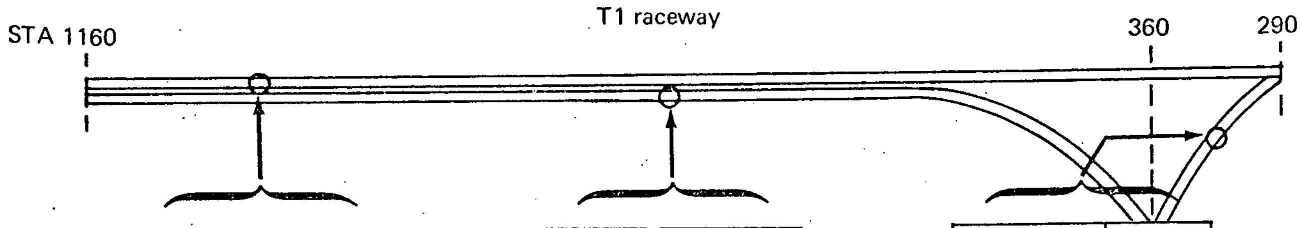
Function	Cost per segment, $
Engineering	3.33
Operations	6.670
Mockup	1.32
Tooling and production planning	0.202
Fabrication and assembly	3.748
Installation	1.400
Total	10.00

COST COMPARISON

To compare the various configurations against the basic conventional round wire system, it was necessary to be able to directly compare each configuration, function by function. It was at first considered practical to select typical bundles and establish cost variation factors for each using RCC, SGW, FCC, and their variations. Typical bundles representing a long run, a medium run, and a short run were selected (fig. 6). This approach was determined as being too involved and no more accurate than comparing a single bundle for each of the configurations (RCC, SGW, FCC, and their variations).

A standard RCC wire bundle 10 ft long and consisting of 55 wires branching into two circuits of 33 wires and 22 wires, respectively, was selected as the basis for comparison. The standard bundle, two SGW bundles, and an FCC bundle, all with the same wire count, are shown in figures 7 through 10. The four configurations shown, along with four others, were evaluated for costs of engineering, operations, and materials. The eight configurations are as follows:

(1)	Standard RCC	This represents the basic or standard RCC bundle (fig. 7) on which the cost rates were established in table 6.
(2)	SGW-1	This is a small-gage wire bundle with braided jacket and stress relief tensile member (fig. 8).
(3)	SGW-2	This small-gage wire bundle has a braided jacket transitioned to a convoluted-tubing jacket for the last 8 in. of the bundle run (fig. 9).
(4)	FCC-TS-1	This is a FCC bundle with transition splices (TS) to RCC so as to enable conventional RCC connectors to be used. The TS will be the same as configuration 1 developed in phase I of this program (fig. 10).
(5)	FCC-TS-2	This is similar to configuration 4 above, but the splice joints are welded.
(6)	FCC-TS-3	The transition splice in this case is per configuration 3 (MTSM) developed in phase I of this program.
(7)	FCC-D-1	This is a FCC installation directly terminated in FCC connectors. The connectors are the crimp-through insulation type (A-MP Unyt) as installed in the 727-100 mockup installation.

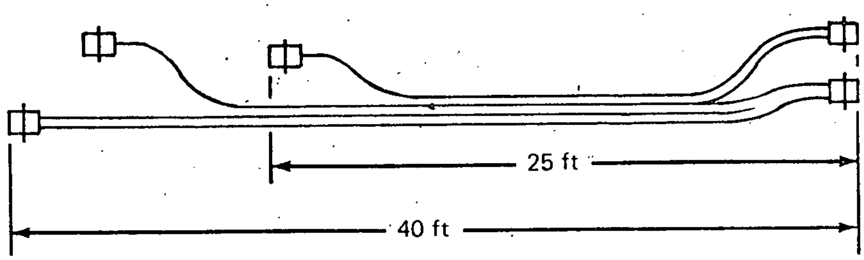


Wire size, AWG	Wires
20	35
22	46
Misc	29
Total wires	110
Length, ft	75

Wire size, AWG	Wires
20	31
22	41
Misc	6
Total wires	78
Length, ft	73

Wire size, AWG	Wires
20	3
22	72
Misc	2
Total wires	77
Length, ft	12

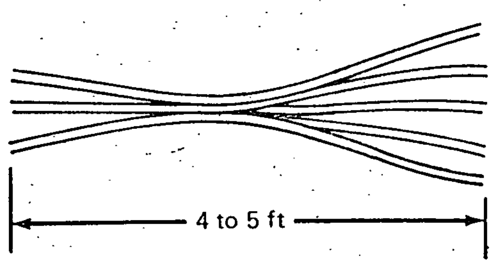
Long (Point-To-Point) Bundle



Cargo compartment bundle W0154-067
(P2-P5-E3-3 to right wing disconnect)

Wire size, AWG	Wires
24	43
22	45
20	29
18	1
16	2
Total wires	120
Length, ft	
59 wires	25
61 wires	40

Medium-Length Bundle



Bundle W0002 (P2 center to cockpit instrument panel)

Wire size, AWG	Wires
24	20
22	171
20	99
18	1
16	9
14	1
Specials	27
Total wires	329
Length (avg), ft	4

Short-Length Bundle

FIGURE 6.—TYPICAL BUNDLES

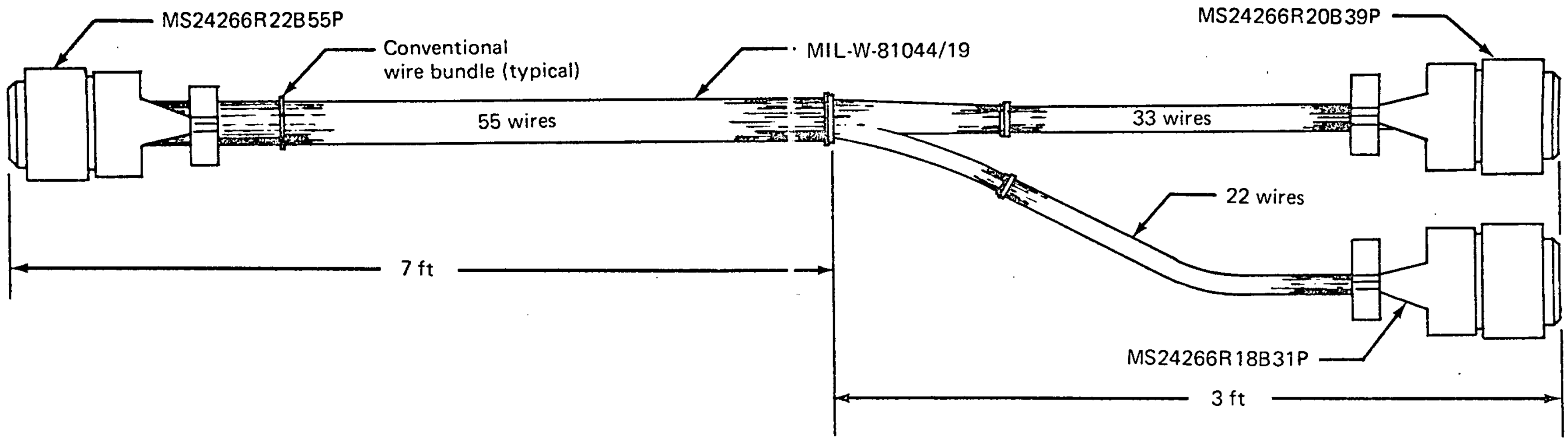


FIGURE 7.—STANDARD RCC WIRE BUNDLE

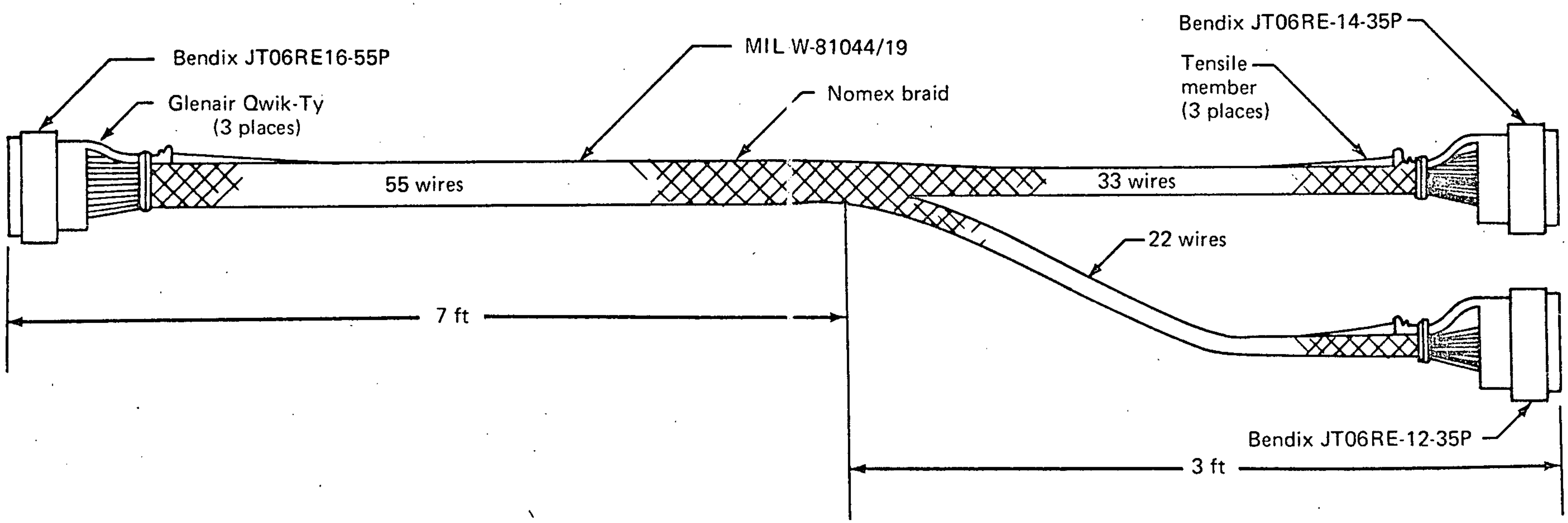


FIGURE 8.—HARNESS—SGW-1

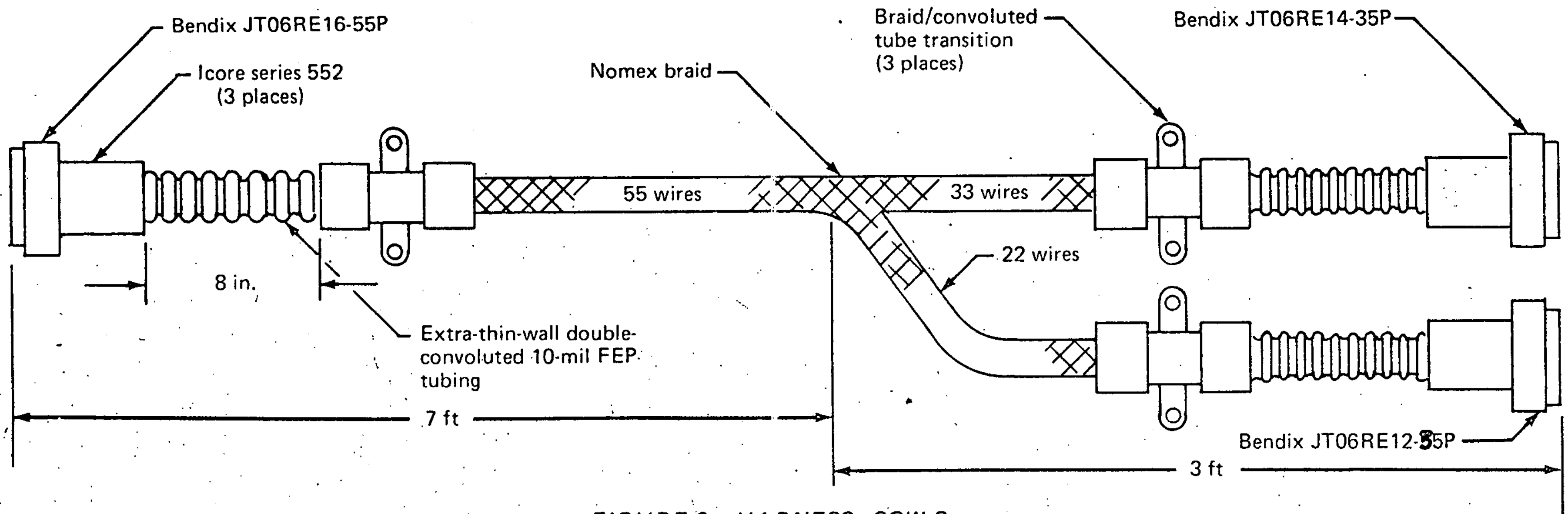


FIGURE 9.—HARNESS—SGW-2

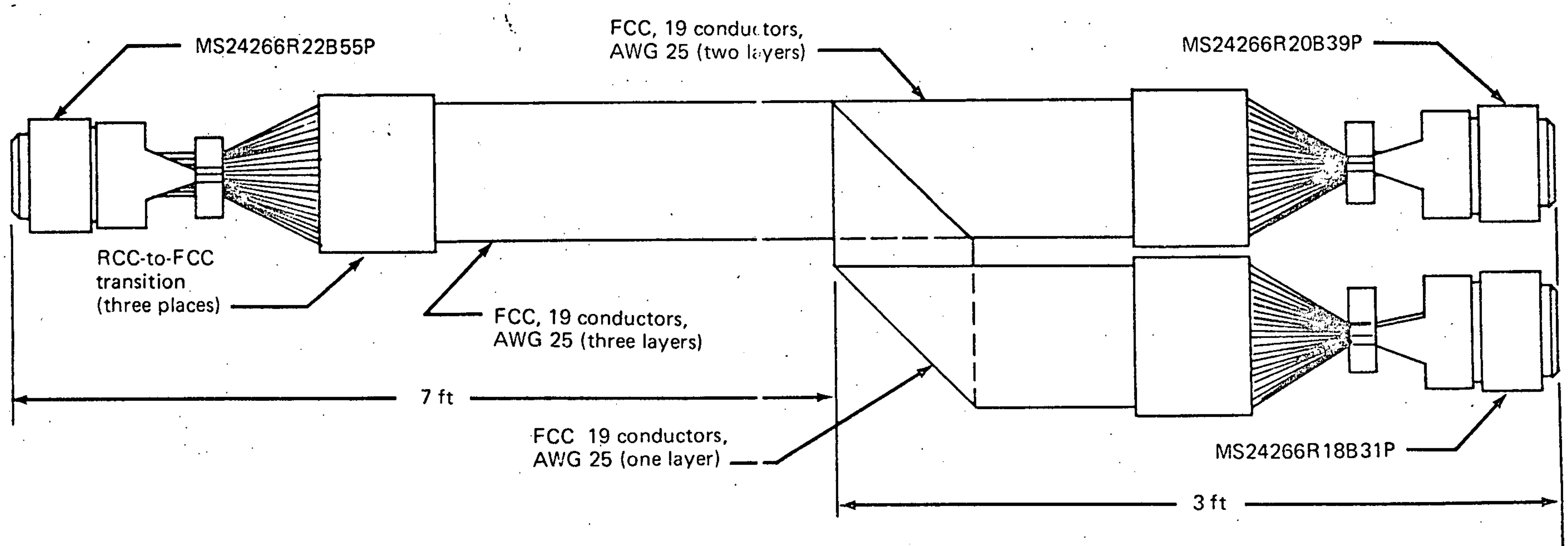


FIGURE 10.—HARNESS FCC-TS-1

(8) FCC-D-2 This is similar to configuration 7 above, but in this case a three-wafer Cannon connector with welded terminations and potted connector grommet is used.

ENGINEERING AND OPERATIONS LABOR COST EVALUATION

Engineering Labor

The evaluation was conducted by comparing each configuration with the standard configuration and assessing the impact on electrical and electronic integration wiring diagrams, data processing, and installation (table 7).

TABLE 7.—ENGINEERING LABOR—EVALUATION

Configuration		Discussion	Cost per segment, $
No.	Type		
1	Standard RCC	This was established as basic in table 6.	3.30
2	SGW-1	Additional workload is imposed on electrical/electronic design—identify circuit function and assign to multiconductor cable configuration; also, set up standards and materials for design of multiconductor cable.	3.60
3	SGW-2	Same as configuration 2.	3.60
4	FCC-TS-1	FCC design will require a uniquely higher engineering startup cost to ensure that circuit assignments within layers and bundles are compatible. This will result in lower long-term costs in such engineering areas as EMC and laboratory and airplane tests; necessity of engineering rework would be reduced. Also, standards and processes will be required for support of the transition splice (TS) and the RCC termination.	3.50
5	FCC-TS-2	Same as configuration 4.	3.50
6	FCC-TS-3	Same as configuration 4.	3.50
7	FCC-D-1	Same as configuration 4, except the TS design is eliminated. There will be some startup component and process requirements related to the FCC connectors, but, in the long term, these will have negligible cost impact.	3.40
8	FCC-D-2	Same as configuration 7.	3.40

Operations Labor

This evaluation is subdivided into the functions of mockup, tooling and production planning, fabrication and assembly, and installation.

Mockup

The mockup is a necessary tool for finalizing design, routing, and bundle integration. Modifications are exercised and verified in the mockup (table 8).

Tooling and Production Planning

Consideration is given to the factors of tooling, production aids, and the ability of a bundle configuration to "flow" along the production system (table 9).

TABLE 8.–OPERATIONS (MOCKUP) LABOR–EVALUATION

Configuration		Discussion	Cost per segment, $
No.	Type		
1	Standard RCC	This was established as basic in table 6.	1.32
2	SGW-1	There is additional work involved due to the preformed cable and structure tiedown for tensile relief. There is also a learning cycle.	1.40
3	SGW-2	Same as configuration 2 but even more involved with transition adaptor tiedown and convoluted ends.	1.55
4	FCC-TS-1	With FCC, routing and identification are reduced considerably.	1.10
5	FCC-TS-2	Same as configuration 4.	1.10
6	FCC-TS-3	Same as configuration 4.	1.10
7	FCC-D-1	All routing, clamping, etc., can be carried out quickly.	1.00
8	FCC-D-2	Same as configuration 7.	1.00

TABLE 9.–OPERATIONS (TOOLING AND PRODUCTION PLANNING) LABOR–EVALUATION

Configuration		Discussion	Cost per segment, $
No.	Type		
1	Standard RCC	This was established as basic in table 6.	0.202
2	SGW-1	The SGW requirements would mean additional tooling–braiders, high-density connector tools, identification sleeves, and crimp tools for both the contacts and the stress wire.	0.30
3	SGW-2	Same as configuration 2 but additional tooling is needed to accommodate the convoluted tubing requirements.	0.35
4	FCC-TS-1	Additional tooling is needed for the FCC, but this is adequately compensated for by the reduction in such facilities as form boards and production floor space; storage facilities and planning are also reduced.	0.16
5	FCC-TS-2	Same as configuration 4 but more production controls are needed in the welding operation.	0.18
6	FCC-TS-3	Same as configuration 4 but more production control.	0.17
7	FCC-D-1	Same as configuration 4 but with direct automatic terminations, which would result in simpler production planning and control.	0.15
8	FCC-D-2	Same as configuration 7, but, with welded terminations, more control is required.	0.16

Fabrication and Assembly

The fabrication and assembly of bundle configurations 1 through 5 was analyzed and timed in the laboratory; times for the other three bundle configurations were calculated from data available from the 727-100 mockup installation (table 10).

Installation

All factors connected with installation of the bundles in the vehicle were compared. These included routing, cable clamping, tiedown, and ease of connector mating (table 11).

TABLE 10.—OPERATIONS (FABRICATION AND ASSEMBLY) LABOR—EVALUATION

Configuration		Discussion	Laboratory man-hours	Configuration factor[a]	Cost per segment, $
No.	Type				
1	Standard RCC	This was established as basic in table 6.	5.75	1	3.748
2	SGW-1	The braiding operations with the breakout and the assembly of the connector (high density) are more time consuming. Some additional training of personnel is required. Identification is more difficult. Rework is a higher factor.	6.25	1.084	4.10
3	SGW-2	Same as configuration 2 but with additional processing of the braid to convoluted tubing transition and the convoluted tubing to connector adaptor. Some additional training required.	7.50	1.3	4.88
4	FCC-TS-1	Cable preparation is substantially reduced (no stripping, no coding), identification is reduced, and automatic crimping is rapid. Very little additional training is required.	4.07	0.817	3.06
5	FCC-TS-2	With this transition splice, the FCC must be stripped, cleaned, and the conductor formed for welding the RCC. The encapsulation will be the same as configuration 4.	5.20	0.905	3.42
6	FCC-TS-3	The advantages of little cutting, coding, and identification are present, but the FCC must be stripped and prepared before insertion into the MTSM. Processing of the MTSM is achieved simply and controlled automatically.	3.7	0.65	2.43
7	FCC-D-1	Same as configuration 6, but no stripping, cleaning, or coding identification are required. Also, it can be terminated directly on an automatic crimp machine.	0.50	0.087	0.326
8	FCC-D-2	No coding and minimum identification are needed. Gang stripping and some preparation are required for welding the contacts.	1.75	0.304	1.14

[a]Configuration n/configuration 1

TABLE 11.–OPERATIONS (INSTALLATION) LABOR–EVALUATION

Configuration		Discussion	Cost per segment, $
No.	Type		
1	Standard RCC	This was established as basic in table 6.	1.40
2	SGW-1	The need for tensile relief tiedowns is an additional requirement. Difficulty of connector rework is another factor.	1.60
3	SGW-2	The braid-to-convoluted-tubing tiedown is an additional requirement over configuration 2, but this is compensated for by ease of rework.	1.60
4	FCC-TS-1	FCC routing with D-clamps is relatively simple.	1.00
5	FCC-TS-2	Same as configuration 4.	1.00
6	FCC-TS-3	Same as configuration 4.	1.00
7	FCC-D-1	All the advantages of configuration 4 are present without the transition splice to round connectors. Considered simpler to install in every way.	0.70
8	FCC-D-2	Same as configuration 7.	0.70

Engineering and Operations Labor Cost Summary

The engineering and operations evaluation emphasizes that engineering and fabrication and assembly are two functions that consume a large proportion of the total cost. Where these functions can be simplified, very significant cost savings are achieved. This is clearly evident in table 12, which summarizes the evaluation.

TABLE 12.–COST COMPARISON SUMMARY–ENGINEERING AND OPERATIONS

Function	Configuration							
	1	2	3	4	5	6	7	8
	Cost per segment, $							
Engineering	3.33	3.60	3.60	3.60	3.50	3.50	3.40	3.40
Operations								
Mockup	1.32	1.40	1.55	1.10	1.10	1.00	1.00	1.00
Tooling and production planning	0.202	0.30	0.35	0.16	0.18	0.17	0.15	0.16
Fabrication and assembly	3.748	4.10	4.88	3.06	2.43	3.42	0.326	1.14
Installation	1.40	1.60	1.60	1.00	1.00	1.00	0.70	0.70
Total	10.00	11.00	11.98	8.92	8.21	9.19	5.556	6.40

MATERIAL COST EVALUATION

The approach taken for this material cost evaluation was to (a) derive a basic material average cost per segment for standard RCC wiring of a complete commercial vehicle that is similar in size to the space shuttle, (b) establish a correction factor by analyzing itemized costs of materials for a specific typical bundle design for all the new technology configurations and comparing them with the costs of the standard configuration of the same bundle design, and (c) project a cost per segment for each new technology configuration by taking the basic cost per segment for standard RCC from (a) and multiplying by the correction factor established in (b).

Basic Costs

One method of deriving basic costs of standard RCC wiring for a similar-sized vehicle is to use actual production cost figures. These costs were normally separated into specialized costs (developmental, tooling, etc.) and production parts costs. The data available varied with the size of the production run, but the following are typical:

Special costs	
Developmental (related to materials only)	\$ 9 000.00
Tooling (special production tooling)	\$ 2 000.00
Purchased equipment (special for the project only)	\$ 5 000.00
Total special costs	\$16 000.00
Production part costs	\$48 000.00

Another method of arriving at a total material cost figure is to itemize costs based on 127 500 ft of wire and 2000 connectors. Approximately 110 000 ft of the wire consisted of AWG 20, 22, and 24, which, for BMS 13-42 (MIL-W-81044), would have an average cost of \$62.50/1000 ft or a total of \$6875. The balance of the wire would be larger sizes and specials, i.e., 20,000 ft at \$150.00/1000 ft for a total of \$3000. For 2000 connectors (MIL-C-26500), at \$22 per mated pair, the cost would be \$44 000. Thus, the total for production parts would be \$53 875.

The above two material cost totals for production parts can now be averaged to (48 000 + 53 875)/2 = \$50 937. Add total special costs of \$16 000 to give total material costs for standard wire per vehicle of \$66 937. Then, for 18 500 wire segments, the total material cost per segment is

$$\frac{\$66\ 937}{18\ 500} = \$3.618 \text{ per segment}$$

This established the costs for standard RCC wiring on a complete vehicle as

Real material cost	\$66 937
Real cost per segment	\$ 3.618

Configuration Correction Factor Analysis

Eight configurations were defined at the beginning of the cost comparision discussion. These configurations were analyzed on the basis of material cost to establish correction factors to be used in deriving new technology configuration real costs.

Because materials are affected by bundle or segment length, all configurations were compared for lengths of 5, 10, 30, and 75 ft to obtain a measure of cost variation. Tables 13 through 20 show the results for each configuration. The cost per average segment is also shown in the tables. (The average segment length was 6.9 ft, based on 18 500 segments and 127 500 ft of wire.)

TABLE 13.–COST–CONFIGURATION 1 (STANDARD RCC)

Material	Bundle length, ft			
	5	10	30	75
Wire (MIL-W-81044)	\$ 18.01	\$ 36.03	\$108.09	\$270.22
Connectors (MIL-C-26500)				
Shell size 22 (mated)	15.02	15.02	15.02	15.02
Shell size 20 (mated)	16.60	16.60	16.60	16.60
Shell size 18 (mated)	14.84	14.84	14.84	14.84
Total material cost	\$ 64.47	\$ 82.49	\$154.53	\$316.68
Cost per segment	\$ 1.17	\$ 1.50	\$ 2.81	\$ 5.75
Cost per average (6.9 ft) segment	\$1.29			

TABLE 14.–COST–CONFIGURATION 2 (SGW-1)

Material	Bundle length, ft			
	5	10	30	75
Wire (MIL-W-81044)	\$ 12.50	\$ 25.00	\$ 75.00	\$187.50
Braid (Nomex)	1.60	3.20	9.60	24.00
Tensile member	0.30	0.60	1.80	4.80
Backshell (Qwik-Ty)	2.19	2.19	2.19	2.19
Connector (MIL-C-38999)				
Shell size 14 (mated pair)	55.48	55.48	55.48	55.48
Shell size 12 (mated pair)	56.26	56.26	56.26	56.26
Shell size 16 (mated pair)	72.26	72.26	72.26	72.26
Total material cost	\$200.59	\$214.99	\$272.59	\$402.56
Cost per segment	\$ 3.64	\$ 3.90	\$ 4.94	\$ 7.31
Cost per average (6.9 ft) segment	\$3.76			

TABLE 15.—COST—CONFIGURATION 3 (SGW-2)

Material	Bundle length, ft			
	5	10	30	75
Wire (MIL-W-81381)	$ 12.50	$ 25.00	$ 75.00	$187.50
Braid (Nomex)	1.28	2.56	7.68	19.20
Backshell adaptors	29.64	29.64	29.64	29.64
Convoluted tubing	5.40	5.40	5.40	5.40
Braid-to-convoluted tubing transitions	30.00	30.00	30.00	30.00
Connector (MIL-C-38999)				
Shell size 12 (pair)	55.48	55.48	55.48	55.48
Shell size 14 (pair)	56.26	56.26	56.26	56.26
Shell size 16 (pair)	72.26	72.26	72.26	72.26
Total material cost	$262.82	$276.60	$331.72	$455.74
Cost per segment	$ 4.77	$ 5.02	$ 6.02	$ 8.30
Cost per average (6.9 ft) segment	$4.85			

TABLE 16.—COST—CONFIGURATION 4 (FCC-TS-1)

Material	Bundle length, ft			
	5	10	30	75
FCC	$ 20.00	$ 40.00	$120.00	$300.00
FCC-to-RCC transitions	11.40	11.40	11.40	11.40
Connectors (MIL-C-26500)				
Shell size 22 (pair)	14.86	14.86	14.86	14.86
Shell size 20 (pair)	19.10	19.10	19.10	19.10
Shell size 18 (pair)	14.84	14.84	14.84	14.84
Total material cost	$ 80.20	$100.20	$180.20	$360.20
Cost per segment	$ 1.46	$ 1.83	$ 3.28	$ 6.55
Cost per average (6.9 ft) segment	$1.60			

TABLE 17.—COST—CONFIGURATION 5 (FCC-TS-2)

Material	Bundle length, ft			
	5	10	30	75
FCC	$ 20.00	$ 40.00	$120.00	$300.00
FCC-to-RCC weld transitions	5.70	5.70	5.70	5.70
Connectors (MIL-C-26500)				
Shell size 22 (pair)	14.86	14.86	14.86	14.86
Shell size 20 (pair)	19.10	19.10	19.10	19.10
Shell size 18 (pair)	14.84	14.84	14.84	14.84
Total material cost	$ 74.50	$114.50	$174.50	$354.50
Cost per segment	$ 1.35	$ 2.09	$ 3.16	$ 6.46
Cost per average (6.9 ft) segment	$1.75			

TABLE 18.–COST–CONFIGURATION 6 (FCC-TS-3)

Material	Bundle length, ft			
	5	10	30	75
FCC	$ 20.00	$ 40.00	$120.00	$300.00
MTSM FCC-to-RCC transitions	18.00	18.00	18.00	18.00
Connectors (MIL-C-26500)				
Shell size 22 (pair)	14.86	14.86	14.86	14.86
Shell size 20 (pair)	19.10	19.10	19.10	19.10
Shell size 18 (pair)	14.84	14.84	14.84	14.84
Total material cost	$ 86.80	$106.80	$186.80	$366.80
Cost per segment	$ 1.56	$ 1.93	$ 3.88	$ 6.67
Cost per average (6.9 ft) segment	$1.73			

TABLE 19.–COST–CONFIGURATION 7 (FCC-D-1)

Material	Bundle length, ft			
	5	10	30	75
FCC	$ 24.00	$ 48.00	$144.00	$ 36.00
Connectors (A-MP)[a]	180.00	180.00	180.00	180.00
Total material cost	$204.00	$228.00	$324.00	$540.00
Cost per segment	$ 3.71	$ 4.16	$ 5.83	$ 9.80
Cost per average (6.9 ft) segment	$3.87			

[a]A-MP price quotes reduced by 64% and based on three mated pairs per bundle.

TABLE 20.–COST–CONFIGURATION 8 (FCC-D-2)

Material	Bundle length, ft			
	5	10	30	75
FCC	$ 24.00	$ 48.00	$144.00	$360.00
Connectors (Cannon)[a]	270.00	270.00	270.00	270.00
Total material cost	$294.00	$318.00	$414.00	$630.00
Cost per segment	$ 5.34	$ 5.80	$ 7.50	$ 11.50
Cost per average (6.9 ft) segment	$5.52			

[a]Cannon price quotes reduced by 50% and based on three mated pairs per bundle.

The material costs per average segment obtained in the foregoing do not include the fixed costs per vehicle (special costs of $16 000 discussed in "Basic Costs"). This, reduced to fixed cost per segment, is $16 000/18 500 or $0.87, which is added to the cost per average segment in table 21 to give the total cost per average segment. For configuration 2, for example, the corrected cost per average segment is $3.76 + $0.87 = $4.63.

TABLE 21.—MATERIAL COST SUMMARY

Item	Configuration							
	1	2	3	4	5	6	7	8
Cost per average segment Fixed cost per segment	$1.29 0.87	$3.76 0.87	$4.85 0.87	$1.60 0.87	$1.75 0.87	$1.73 0.87	$3.87 0.87	$5.52 0.87
Total cost per average segment	$2.16	$4.63	$5.72	$2.47	$2.62	$2.60	$4.74	$6.39
Correction factor $= \frac{\text{configuration } n}{\text{configuration } 1}$	1	2.14	2.65	1.14	1.22	1.20	2.19	2.96
"Real" cost per segment	$3.618	$7.74	$9.59	$4.12	$4.41	$4.34	$7.92	$10.71

The above analysis provides the total cost per average segment for both standard RCC and the new technology configurations. The correction factor is then derived by comparing each new technology configuration with the standard RCC configuration.

Real Cost Per Configuration Segment

Configuration "real" cost per segment was calculated by applying its correction factor to the "real" cost per segment for standard RCC wiring ($3.618 established previously). For example, for configuration 2, "real" cost per segment = 2.14 x 3.618 = $7.74. Table 21 shows the real cost per segment for all configurations.

TOTAL COST SUMMARY

The engineering and operations analysis resulted in labor costs per segment for each of the eight configurations. The materials analysis produced the "real" material cost per segment. Table 22 projects the total cost per segment (labor plus materials).

TABLE 22.—TOTAL COST SUMMARY

Item	Configuration							
	1	2	3	4	5	6	7	8
Labor cost per segment Material cost per segment	$10.000 3.618	$11.00 7.74	$11.98 9.59	$ 8.92 4.12	$18.21 4.41	$ 9.19 4.34	$. 5.56 7.92	$ 6.40 10.70
Total cost per segment	$13.618	$18.74	$21.57	$13.04	$12.62	$13.53	$13.48	$17.10

WEIGHT/COST EVALUATION

Weight analyses were performed for each of the eight bundle configurations (tables 23 through 27) as well as for the total vehicle (table 28). These analyses assume the following special factors.

- The study was limited to 110 000 ft of wire, which represented the conventional application of AWG 20, 22, and 24 only, and considered an equal division between these gages.
- In all cases, the connector weights were doubled to represent mated pairs.
- Connector population per bundle was adjusted from the three mated pairs used in the sample bundle to 10 mated pairs to result in a total vehicle connector count of 2000 mated pairs.
- For configurations 2 and 3, conventional wire was used for AWG 20 and 22 applications and only the AWG 24 wire was replaced with SGW.
- In the case of FCC applications, some liberties were taken with gage sizes as listed below:

Conventional Wire Size, AWG	FCC Wire Size, AWG
20	21
22	25
24	28

- For the total vehicle wire weight, 200 wire bundles per configuration, each 10 ft long and having 55 circuits, were considered.

Data from previous analyses were projected for manufacturing wiring cost per vehicle, weight per vehicle, and operation cost per vehicle based on 10 missions and total value of technology for the various harness configurations. The following factors were used in this cost study:

- Usage factors and gage size restrictions similar to those used in the weight analysis were imposed.
- All gages of FCC (21, 25, and 28) and their associated connectors were considered of equal cost.
- Costs were reduced for both unsealed and sealed FCC connectors from those quoted by manufacturers to account for production implementation.

TABLE 23.—WEIGHT ANALYSIS—CONFIGURATION 1 (STANDARD RCC)[a]

Item	Description or calculation	Connector weight per mated pair, lb	Qty	Item weight, lb
AWG 24, MIL-W-81044/19				
MS24266R22B55P	Connectors with clamps and contacts	0.324	2	0.648
MS24266R20B39P		0.272	3	0.816
MS24266R18B31P		0.206	5	1.030
Wire	(2.2 lb/1000 ft) (550 ft)	–	–	1.210
		Total bundle weight		3.704
AWG 22, MIL-W-81044/16				
MS24266R22B55P	Same as above	0.324	2	0.648
MS24266R20B39P		0.272	3	0.816
MS24266R18B31P		0.206	5	1.030
Wire	(3.2 lb/1000 ft) (550 ft)	–	–	1.760
		Total bundle weight		4.254
AWG 20, MIL-W-81044/16				
MS24266R22B55P	Same as above	0.324	2	0.648
MS24266R20B39P		0.272	3	0.816
MS24266R18B31P		0.206	5	1.030
Wire	(4.7 lb/1000 ft) (550 ft)	–	–	2.585
		Total bundle weight		5.079

[a]Standard RCC configuration bundle is 10 ft long with 55 wires (fig. 7).

TABLE 24.—WEIGHT ANALYSIS—CONFIGURATION 2 (SGW-1)[a]

Item	Description or calculation	Connector weight per mated pair, lb	Qty	Item weight, lb
AWG 30				
JT06RE 16-55P	Connectors with contacts	0.0990	2	0.1980
JT06RE 14-35P		0.0814	3	0.2442
JT06RE 12-35P		0.0686	5	0.3180
Wire	(0.54 lb/1000 ft) (550 ft)	–	–	0.2970
Nomex braid	(9.16 lb/1000 ft) (25 ft)	–	–	0.2290
GTR84-16Y	Connector backshells	–	2	0.0540
GTR84-14Y		–	3	0.0750
GTR84-12Y		–	5	0.1100
Tensile wire	(1.7 lb/1000 ft) (20 ft)	–	–	0.0340
		Total bundle weight		1.559

[a]SGW bundle is 10 ft long with 55 wires (fig. 8).

TABLE 25.—WEIGHT ANALYSIS—CONFIGURATION 3 (SGW-2)[a]

Item	Description or calculations	Connector weight per mated pair, lb	Qty	Item weight, lb
JT06RE 16-55P		0.0990	2	0.1980
JT06RE 14-35P	Connector with contacts	0.0814	3	0.2442
JT06RE 12-35P		0.0636	5	0.3180
Wire	(0.540 lb/1000 ft) (550 ft)	–	–	0.2970
Nomex braid	(9.16 lb/1000 ft) (15 ft)	–	–	0.1374
5520-09-123-1		–		
5520-12-143-1	Convoluted tube fittings	–	10	0.2810
5520-12-163-1		–		
5630-09-051-11		–		
5630-12-071-11	Braid adaptors	–	10	0.3320
5630-12-071-11				
Convoluted tubing	(15 lb/1000 ft) (10 ft)	–	–	0.1500
		Total bundle weight		1.9576

[a]SGW bundle is 10 ft long with 55 wires (fig. 9).

TABLE 26.—WEIGHT ANALYSIS—CONFIGURATIONS 4, 5, AND 6 (FCC-TS-1, -2, -3)

Item	Description or calculations	Connector weight per mated pair, lb	Qty	Item weight, lb
		AWG 28		
MS24266R22B55P		0.324	2	0.648
MS24266R20B39P	Connectors with clamps and contacts	0.272	3	0.816
MS24266R18B31P		0.206	5	1.030
Splice box (solder, weld, A-MP crimp)	(10) (0.019 lb)	–	10	0.190
MTSM transition splice	(10) (0.007 lb)	–	10	0.070
Wire (FCC)	–	–	–	0.426
Wire (AWG 24, RCC)	(57) (2.2 lb/1000 ft)	–	–	0.125
		Total bundle weight (with splice boxes)		3.235
		Total bundle weight (with MTSM transitions)		3.115
		AWG 25		
MS24266R22B55P		0.324	2	0.648
MS24266R20B39P	Same as above	0.272	3	0.816
MS24266R18B31P		0.206	5	1.030
Splice box	Same as above	–	10	0.190
MTSM transition	Same as above	–	10	0.070
Wire (FCC)	(27) (32 lb/1000 ft)	–	–	0.864
Wire (AWG 24, RCC)	(57) (2.2 lb/1000 ft)	–	–	0.125
		Total bundle weight (with splice boxes)		3.673
		Total bundle weight (with MTSM transitions)		3.553
		AWG 21		
MS24266R22B55P		0.324	2	0.648
MS24266R20B39P	Same as above	0.272	3	0.816
MS24266R18B31P		0.206	5	1.030
Splice box	Same as above	–	10	0.190
MTSM transition	Same as above	–	10	0.070
Wire (FCC)	–	–	–	1.680
Wire (AWG 20, RCC)	–	–	–	0.182
		Total bundle weight (with splice boxes)		4.546
		Total bundle weight (with MTSM transitions)		4.426

[a]Total FCC bundle is 10 ft long with 57 conductors (fig. 10).

TABLE 27.—WEIGHT ANALYSIS—CONFIGURATIONS 7 AND 8 (FCC-D-1, -2)

Item	Description or calculation	Connector weight per mated pair, lb	Qty	Item weight, lb
AWG 28, 51 conductors				
A-MP connectors	–	0.2646	10	2.646
ITT Cannon connectors	–	0.1874	10	1.874
Wire (FCC, 17-conductor tape)	(30 ft) (14.2 lb/1000 ft)	–	–	0.429
		Total bundle weight (with A-MP connectors)		3.075
		Total bundle weight (with ITT Cannon connectors)		2.303
AWG 25, 57 conductors				
A-MP connectors	–	0.2646	10	2.646
ITT Cannon connectors	–	0.1874	10	1.874
Wire (FCC, 19-conductor tape)	(30 ft) (32 lb/1000 ft)	–	–	0.960
		Total bundle weight (with A-MP connectors)		3.606
		Total bundle weight (with ITT Cannon connectors)		2.834
AWG 21, 54 conductors				
A-MP connectors	–	0.2646	10	2.646
ITT Cannon connectors	–	0.1874	10	1.874
Wire (FCC, 9-conductor tape)	(60 ft) (31.2 lb/1000 ft)	–	–	1.870
		Total bundle weight (with A-MP connectors)		4.516
		Total bundle weight (with ITT Cannon connectors)		3.744

TABLE 28.—TOTAL VEHICLE WIRING WEIGHT[a]

Configuration	AWG	Weight per 10 ft of bundle, lb	Vehicle wiring weight, lb	Delta weight, lb	Reference table
1	20	5.079	335.21	Ref	23
	22	4.254	285.02		
	24	3.704	248.17		
		Total	868.4		
2	20	5.079	335.21	143.67	24
	22	4.254	285.02		
	SGW	1.559	104.50		
		Total	724.73		
3	20	5.079	335.21	117.01	25
	22	4.254	285.02		
	SGW	1.958	131.16		
		Total	751.39		
4,5	21 (FCC)	4.546	300.04	105.52	26
	25 (FCC)	3.673	246.09		
	28 (FCC)	3.235	216.70		
		Total	762.88		
6	21 (FCC)	4.426	292.12	129.52	26
	25 (FCC)	3.553	238.05		
	28 (FCC)	3.15	208.71		
		Total	238.88		
7	21 (FCC)	4.516	298.1	122.70	27
	25 (FCC)	3.606	241.6		
	28 (FCC)	3.075	206.0		
		Total	745.7		
8	21 (FCC)	3.744	247.1	277.10	27
	25 (FCC)	2.834	189.9		
	28 (FCC)	2.203	154.3		
		Total	591.3		

[a]A total of 110 000 ft of AWG 20, 22, and 24 RCC is used for conventional wire.
A typical bundle is 10 ft long and has 55 circuits and 10 connectors (mated pairs)
There are 200 bundles and 2000 connectors per vehicle.

Table 29 summarizes the cost projection.

To arrive at the optimum choice of harness configuration for application to a vehicle such as the space shuttle, the total value of technology was considered as the figure of merit desired. Total value of technology is defined as the total of wiring manufacturing costs per vehicle plus the cost impact of vehicle weight on payload per mission multiplied by ten missions. The mission cost is to be based on the cumulative average mission cost over the program life of 15 years.

Space shuttle program cost impact of vehicle weight on payload per mission, based on data from the NASA planning estimate for the 15-year space shuttle effort dated March 1972, are as follows:

Total budget through first flight (1978)	$\$5.5 \times 10^9$
Follow-on 10-year program costs covering additional vehicles and 450 flights	$\$2.0 \times 10^9$
Nominal space shuttle payload—each way	40 000 lb

TABLE 29.–VEHICLE MANUFACTURING WIRING COST DATA–DETAILS[a]

Configuration	Labor cost per segment, $	+	Materials cost per segment, $	=	Total cost per segment, $	x	Number of segments	=	Total cost per vehicle, $
1	10.00		3.61		13.618		16 000		217 904.00
[b]2	11.00		7.74		13.618		10 666		145 260.25
					18.74		5 334		99 959.16
									245 219.41
[b]3	11.98		9.59		13.618		10 669		145 260.25
					21.57		5 334		115 054.38
									260 314.63
4	8.92		4.12		13.04		16 000		208 640.00
5	8.21		4.41		12.62		16 000		201 920.00
6	9.19		4.34		13.53		16 000		216 480.00
7	5.556		7.92		13.48		16 000		215 680.00
8	6.40		10.71		17.10		16 000		273 760.00

[a]Total vehicle wire length is 127 500 ft
There are 18 500 segments per vehicle or an average of 6.9 ft per segment
Of the 18 500 segments, 16 000 are of AWG 20, 22, and 24 wire with a total length of 110 000 ft.
[b]Conventional wiring used with SGW as follows: 10 666 segments of AWG 20 and 22; 5334 segments of AWG 30.

The average cost per flight over 15 years and 451 flights is \$16.67 million per flight. This resolves to a cost per pound of payload per flight of \$416.8 over the 15-year period (fig. 11).

The total value of wiring technology applied to the space shuttle program, as described above, is included as table 30. In analyzing the previous data, it is apparent that the optimum total value of wiring technology for the space shuttle would be achieved if a hybrid of the various wiring harness

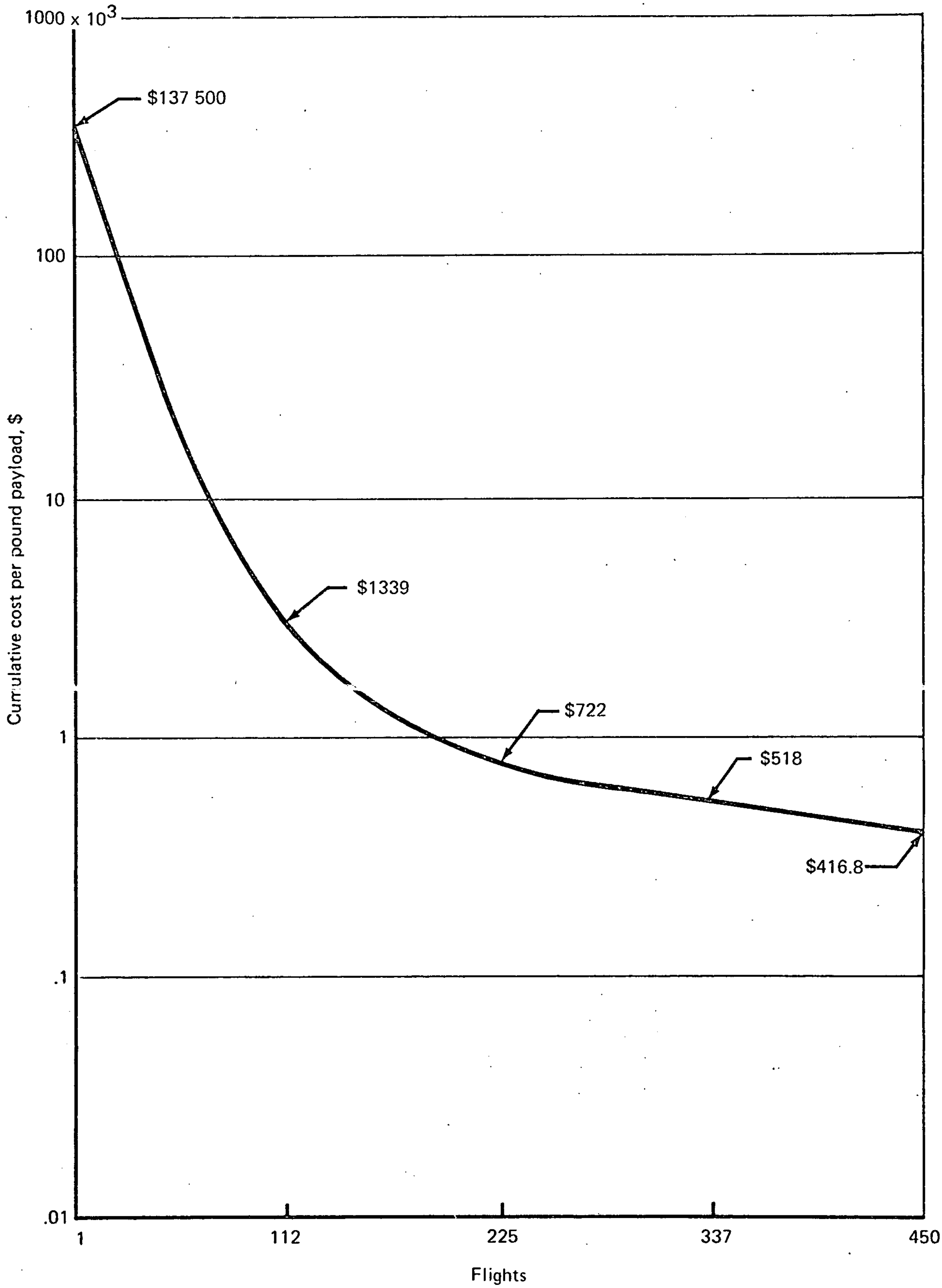


FIGURE 11.—CUMULATIVE COST PER POUND OF PAYLOAD—SPACE SHUTTLE

TABLE 30.—TOTAL VALUE OF VEHICLE WIRING TECHNOLOGY—SUMMARY

Configuration	Vehicle wiring manufacturing cost [a]		Vehicle wiring weight,[a] lb		Cost impact on payload[b]	Total value of technology[c]
	Total	Delta	Total	Delta		
1	$217 904	Ref	868.40	Ref	—	$+217 904
2	$245 219-	$+27 315	724.73	143.67	$ 598 817	$- 353 598
3	$260 315	$+42 411	753.73	114.67	$ 477 944	$-217 630
4	$208 640-	$- 9 264	762.88	-105.52	$ 439 807	$-231 167
5	$201 920-	$- 15 984	762.88	-105.52	$ 439 807	$-237 887
6	$216 480	$- 1 424	738.88	-129.52	$ 539 839	$-323 359
7	$215 680	$- 2 224	745.70	-122.70	$ 511 414	$-295 734
8	$273 760	$+55 856	591.30	-277.10	$1 154 952	$-881 192

[a]Vehicle wiring manufacturing costs and weight totals are limited to 110 000 ft of conventional RCC and do not include "other" types such as larger gages (power circuits), coaxial cables, engine circuits, fire detection wiring, etc.

[b]Based on $416.8/lb of payload and 10 flights per vehicle.

[c](+) indicates program cost based on base payload delivered and (-) indicates cost benefits due to added payload capacity through first 10 flights per vehicle.

TABLE 31.—WIRING WEIGHT—HYBRID SYSTEM

Configuration	Wire size, AWG	Weight, lb
8	21 (FCC)	247.1
8	25 (FCC)	189.9
2	30 (SGW)	104.5
	Total	541.5

868.4 lb (conventional wire weight)
541.5 lb (new technology wire weight)
326.9 lb weight saving

TABLE 32.—MANUFACTURING COSTS—HYBRID SYSTEM

Configuration	Conventional wire size, AWG	Wire segments	New technology wire size, AWG	Cost per segment	Total cost
8	20	5 333	21 (FCC)	$17.10	$ 91 194.30
8	22	5 333	25 (FCC)	27.10	91 194.30
2	24	5 334	30 (SGW)	18.74	99 959.16
	Total	16 000	—	$17.60 (average)	$282 347.76

configurations was used. Therefore, a combination of configuration 2 (SGW-1) and configuration 8 (FCC-D-2) is listed as to weight in table 31 and cost in table 32. The total and net values for the hybrid system are derived as follows:

$$\begin{aligned}
\begin{matrix}\text{Total}\\ \text{value}\end{matrix} &= \begin{pmatrix}\text{Weight}\\ \text{saved}\end{pmatrix}\begin{pmatrix}\text{Payload}\\ \text{cost}\end{pmatrix}\begin{pmatrix}\text{Number}\\ \text{of flights}\end{pmatrix}\\
&= (326.9\ \text{lb})(\$416.8)(10)\\
&= \$1\ 362\ 561
\end{aligned}$$

$$\begin{aligned}
\begin{matrix}\text{Net}\\ \text{value}\end{matrix} &= \begin{pmatrix}\text{Manufacturing}\\ \text{cost}\end{pmatrix} - \begin{pmatrix}\text{Total}\\ \text{value}\end{pmatrix}\\
&= (\$282\ 377) - (\$1\ 362\ 561)\\
&= \$-1\ 080\ 184
\end{aligned}$$

CONCLUSIONS

It was concluded that any new technology wiring within the seven configurations considered will result in a benefit to the total value of technology. Application of these wiring technologies to future air and space vehicles having a cost-impact-of-weight-on-payload factor of $300/lb and above is mandatory. In fact, even with the significant material cost disadvantages for the new technologies, the total results indicate large gains by their application.

Further improvements could be made with timely application of R&D efforts in the areas of:

- FCC connectors
- FCC permanent splice designs and processing
- SGW harness design developments and associated processes
- Follow-on cost studies to evaluate the payoff/penalty considerations of the various factors affected by application of the new technology.

RECOMMENDATIONS FOR FOLLOW-ON

Follow-on studies are required to arrive at more accurate predictions of costs for both conventional and new technology wiring applications for future military air and space programs. A balanced technology R&D effort is needed to ensure advances in wiring such that vehicle wiring systems keep pace with such related systems and components as control systems, advanced displays, remote power controllers, etc. Advanced wiring technology may provide techniques with low risk, reduced weight, and competitive costs per pound, provided adequate cost studies are pursued and documented so that realistic program costs can be monitored. The areas deserving special attention are:

- Engineering costs—As indicated in tables 12 and 29, engineering costs are $3.33 out of a total of $13.618 per segment for conventional RCC wiring (24.5% of the total vehicle manufacturing wiring costs). Detailed cost impact studies are needed to determine sensitivity of engineering cost per segment versus various wiring technologies.

- Fabrication and assembly costs—These costs for conventional wiring are 27.5% of the total costs per segment (tables 12 and 29). Detailed analyses, including industrial engineering time and motion studies, should be conducted to establish more accurate costs for the new wiring technologies.

- Material Costs—The material costs per segment (table 29) vary from 26.5% for conventional wiring to the range of 44% to 67% for some of the new technology wiring. These material costs are excessive. However, they are based on prices that have been reduced a significant amount, arbitrarily, from prices quoted by the suppliers. It has been noted that industry cost reductions have been significant in other areas (standard wire, connectors, microelectronics, etc.) as standards are established and widespread usage occurs. Therefore, this phase of the follow-on program should direct itself to "realistic" predictions of the *time phase* of the new wiring technology materials cost for the 1975 to 1980 period (fig. 12, for example).

- Repair Costs—Repair costs of the various wiring technologies were not studied specifically in this program. Both engineering analysis and industrial engineering studies are needed in this area.

In total, the studies included in this report and the follow-on studies recommended above should be covered using specific baseline data. The data will be applied to evaluate the cost impact of future predicted industry usage of the various technologies (fig. 12) and normal time/inflation cost effects. These, in turn, will be used to more accurately predict a 1975 to 1980 timing of the application of these various wiring technologies to a typical space vehicle program (space shuttle).

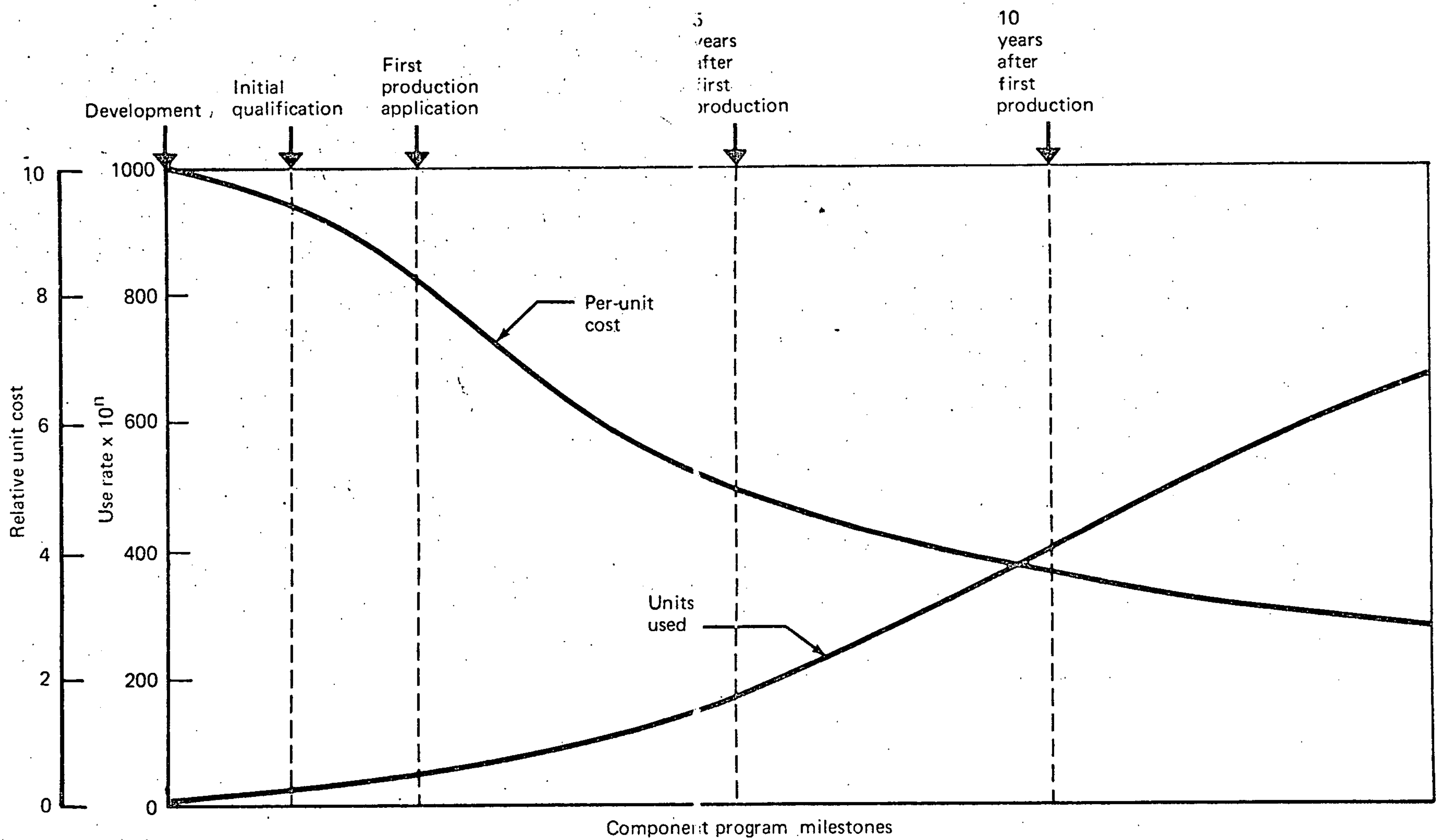


FIGURE 12.—EFFECT OF PREDICTED USE ON UNIT COST